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A Technology for Energy Conservation Using Screw-Rotor Steam Engines

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Abstract—An energy conservation technology is described based on utilizing the energy of steam to produce electricity at an enterprise's boiler house by means of a power installation comprising a screw-rotor steam engine and an asynchronous electric generator.

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The last 10–15 years have witnessed the idea of utilizing the energy of steam to generate electricity at the boiler house of an enterprise for covering its electrical load to have received a growing use. Accordingly, small-capacity (200–2000 kW) steam power units are being developed on the basis of traditional steam turbines (produced by Kaluga Turbine Works, AO Energotekh, and others), as well as those using new types of steam expanders, such as screw-rotor steam engines (SSEs) (produced by AO Nezavisimaya Energetika, AO Generatsiya, AO VM-Energiya, AO Ekoenergetika, and others).

An SSE, as a thermal engine, has essential advantages over blade turbines at small power capacities. However, power units built around SSEs have not yet received wide use. This is mainly due to the following three factors.

First, the SSE is in fact a new type of a steam engine, and both its design and the working process in it must be optimized. Second, the technology for generating electricity at an enterprise's boiler house has not been fully elaborated yet. The principles of large-scale steam power engineering cannot be mechanistically transferred into the field of small-scale steam power engineering [1]. Third, introduction of this new technology is held back by the relatively low costs for fuel (gas, in particular), a factor that results in a longer payback period of a power installation.

The purpose of this study is to generalize the experience accumulated in the use of SSEs, the results of which may give a new stimulus for further development of this avenue.

The author of this paper initiated the idea of creating SSEs back in the 1990s and received more than 20 Russian and foreign patents on this subject. Experimental 200 kW PVM-200 AG and the PVM-2000 AG SSEs have been developed (the latter, the maximum power output of which is equal to 2000 kW, is now passing its pilot commercial operation at Raevsk Sugar Works in Bashkortostan). The PVM-2000 AG has been in operation for 2153 h, its hourly average power output (dictated by steam conditions) is 563 MW, and its maximum power output is 850 kW.

Below, the main principles of such a technology for energy conservation are considered. It is essential to note from the very beginning that the generation of own electricity is a useful, but a side process. The most important thing here is not to disturb the operation of the main production process, which uses steam for its technological needs.

The steam produced in the boilers at industrial boiler houses is generated there at pressures of 0.8–13 MPa and temperatures of 176–194°C, depending on the extent to which the boilers have been worn out and the technology of steam consumption; if a steam superheater is available, this temperature may be as high as 250°C. If this steam is directed to a power installation the part of its thermal energy will be converted into electricity. A certain additional quantity of fuel has to be fired in the boiler in order to compensate for the energy of steam that was taken away. Calculations have shown that the specific consumption of additional (equivalent) fuel for the generated electricity is equal to 140–145 g/(kW h).

The spent steam from an SSE is intended for technological needs or for heating purposes. The temperature of this steam must meet the conditions of a concrete production process, e.g., evaporation of sugar from beet. Since the steam leaving an SSE is wet (according to the laws of thermodynamics), the pressure of this steam unequivocally determines its temperature (Fig. 1).

The relative indicated efficiency of an SSE η_{oi}. It has been shown experimentally [2] that the application of sealing material on the rotors and shell of a screw-rotor machine allows its maximum efficiency $\eta_{oi} = 0.86$ to be obtained. It is noteworthy that this efficiency depends considerably on the screw peripheral velocity, the optimal value of which is in the range from 80 to 100 m/s [3]. Gaps between the rotors are another important factor that affects η_{oi}. The gaps found in

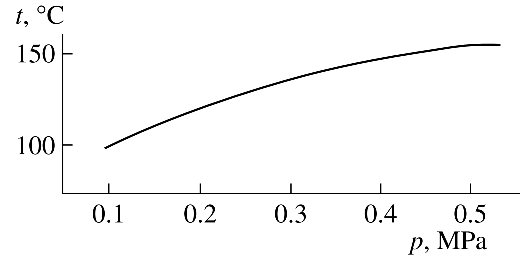

Fig. 1. Wet steam temperature as a function of pressure.

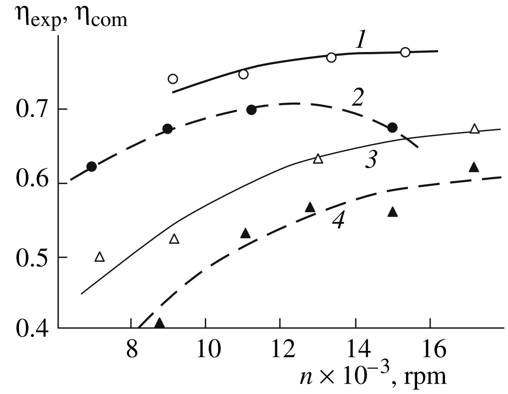

Fig. 2. The effect of the rotation frequency and gaps on the efficiency of a screw-rotor machine for its operation as an expansion engine η_{exp} and as a compressor η_{com}. Gap between the rotors, mm: (*1*) and (*3*) 0.22 and (*2*) and (*4*) 0.29. Operation: (*1*) and (*2*) as an expansion engine, (*3*) and (*4*) as a compressor.

screw-rotor machines that are already in operation are equal to around 0.1% of the screw-rotor diameter [4]. When the machine runs with wet steam, the condensate that is generated during its operation flows into the gaps; this reduces the leaks of steam, thus helping increase η_{oi}. It has been shown experimentally that, if a screw-rotor machine operates as an expansion engine, its efficiency is much higher than in the case when it operates as a compressor (Fig. 2) [5]. In reality, η_{oi} is equal to 0.72–0.76. This value is higher than that found in the small blade turbines: η_{oi} drops as a result of a larger relative gap between the blades and shell. In addition, an increase in the moisture content of steam causes the efficiency of a blade turbine to drop considerably as a result of the higher loss that occurs when such steam flows over a blade profile [6].

Leaks of steam through shaft glands have a considerable effect on the economic efficiency of SSEs. Unlike the large turbines used at thermal power stations, the steam from the labyrinth glands of which is used to reheat the condensate, this cannot be done in small-size installations built around SSEs: steam is discharged into the atmosphere, polluting the environment. The thermal power carried away with steam through the two pairs of glands on both the shafts is commensurable with the electric power output being generated, nullifying all the effect of energy conservation. Thus, leaks of steam through glands are inadmissible; therefore, double end-face glands have to be used in SSEs, which use water as sealing fluid.

Optimality of the SSE design. This is a very important factor, which in fact determines the viability of the power installation. Figure 3 shows a longitudinal section of the patented design of a PVM-2000 along the main rotor. The screw-rotor steam engine belongs to the type of positive-displacement machines. It has a high-pressure shell (HPS) with an inlet connection pipe, a low-pressure shell (LPS) with an outlet connection pipe, and the main and slave screw rotors (the latter cannot be seen in the figure). The shafts are equipped with end seals, as well as with support and thrust bearings. The main and the slave rotors have four and six screw teeth on them, respectively, which are engaged with a guaranteed gap. These rotors, which are interconnected by means of synchronizing gears, are also furnished with the relief gas-dynamic pistons. A centering bottom having an inlet port for admission of live steam is situated in the vertical plane of the joint connecting the HPS to the LPS. The centering bottom allows the HPS and LPS axes to be precisely aligned with each other in the course of assembling the machine. The machine has a horizontal plane of the joint that passes through the axes of both the rotors.

The SSE operates as follows. Live steam, which passes through the inlet port, is admitted to the screw teeth of the rotors, expands in the pockets formed by the teeth cavities, and then is removed from the machine through the exhaust pipe.

Service life and repairs. Naturally, no experimental data on the design service life of SSEs have been obtained yet. However, based on the experience gained from the operation of screw-rotor compressors, machines that are inverted with respect to SSEs, it is possible to establish the service life of SSEs of no less than 150 000–200 000 h (i.e., 25–30 years), since an SSE's screw rotors do not touch each other during operation, nor do they suffer erosion wear on the side of wet steam. The steel rotors and the shell are covered with a black oxide film during operation; i.e., they undergo a sort of blueing.

SSEs are taken for repairs once in every 2–3 years (after 15 000 h of operation), which consist mainly of repairing the sliding bearings and end seals. An SSE is disassembled and assembled by two medium-skilled servicemen within 4–6 days. Once the SSE has been assembled, it must be necessarily aligned with the generator with an accuracy of at least 0.05 mm to avoid the occurrence of vibration.

The system for giving out the electric power. The outlet shaft of the SSE's main rotor is connected to an electric generator. If the unit is supposed to operate in parallel with the electric network (0.4, 6, and 10 kV), it is advisable to use an asynchronous generator (AG), a

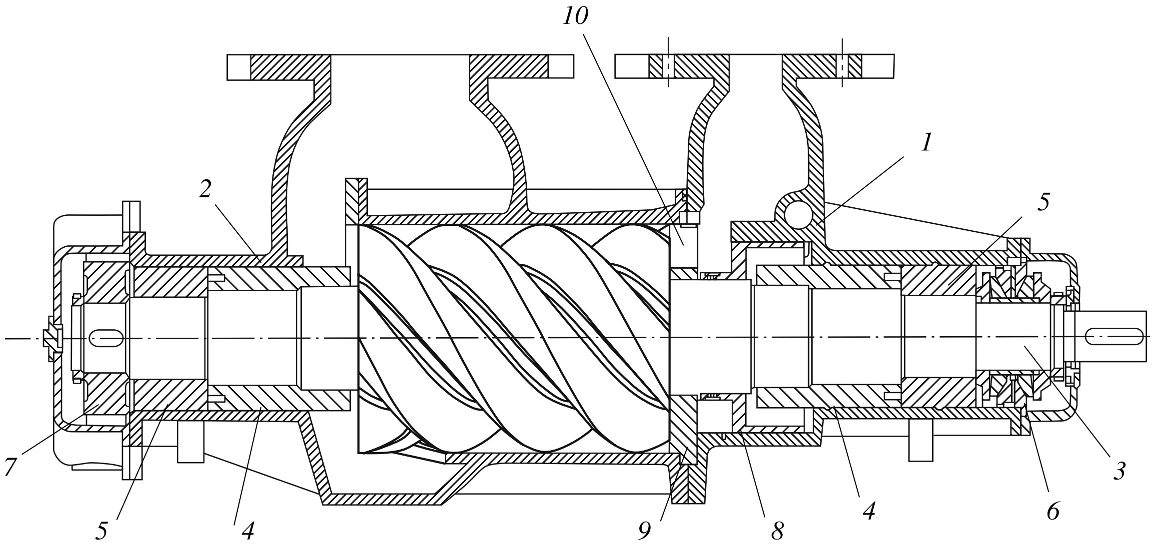

Fig. 3. Design of the PVM-2000 screw-rotor engine. (*1*) HPC; (*2*) LPS, screw rotors; (*3*) main screw rotor; (*4*) end seals; (*5*) support bearings; (*6*) thrust bearings; (*7*) synchronizing gears; (*8*) relief gas-dynamic pistons; (*9*) centering bottom; and (*10*) inlet port.

machine inverted with respect to a usual series-produced squirrel-cage induction motor.

An AG has the following advantages over a synchronous generator (SG):

(i) it is simpler in maintenance and reliable in operation;

(ii) its cost is half that of the SG;

(iii) it does not need a synchronization system, nor does it require a generator excitation controller;

(iv) its protection system is much simpler than that of an SG, because the dying of magnetic field in the rotor causes the short-circuit currents in an AG to decay fairly rapidly; and

(v) the maximum rotational frequency of mass-produced asynchronous machines for capacities of up to 1 MW is 3000 rpm, whereas that of SGs is 1500 rpm. Thus, an AG can operate with an SSE either directly or via a gear having a low gear ratio.

However, an AG has certain drawbacks:

(i) it absorbs reactive power from the network (this can be compensated for by connecting a bank of capacitors on the low-voltage side); and

(ii) it features rather a high level of noise from fan operation, since mass-produced AGs for a capacity of around 1 MW have air cooling.

The pilot commercial operation of the power unit comprising a PVM-2000 screw-rotor steam engine and an AG gave rise to no claims with respect to its electric power part from the power engineers of Raevsk Sugar Works.

Difficulties are frequently encountered when attempts are made to agree upon technical specifications for connecting AGs to the network. Enterprises supplying electric power to consumers are not interested in dealing with cases in which electric power is supplied to the network beyond the confines of an enterprise. The production of electricity at a boiler house should therefore be aimed at meeting only the needs of the enterprise itself.

The automatic control and protection system (ACPS). This system must automatically protect the power installation if an emergency situation occurs. The protective action consists in stopping the supply steam to the SSE and simultaneously disconnecting the generator from the network. The protection system is placed at the central control board of the boiler house and comprises a control console built around an industrial computer. Normal starting and shutdown of the SSE are carried out manually from this console; the power output is adjusted using a slide valve at the inlet of steam to the SSE. The rotation frequency remains almost invariable during this adjustment, since the AG rotation frequency is determined by the power network frequency.

The use of such a power installation at a boiler house should not disturb the supply of steam to the main production process of an enterprise, nor should it affect the operation of the boilers. This generates the need to install an automatic steam switch at the inlet of steam to the SSE, which must be connected to the ACPS. If an emergency situation occurs, the switch immediately stops the admission of steam to the SSE and directs it through a reducing device to the main production process.

System for cooling oil and gland water in seals. The flowrate of water for cooling oil and gland water in seals should be kept to a minimum, since it has a considerable effect on the economic efficiency of the power installation. The cooling system itself must be compact, simple, and reliable.

The drawbacks of an air-cooling system consist in that the fan generates considerable noise during its operation and that it is difficult to ensure the required thermal conditions of the installation during the hottest spells in summer. On the other hand, a return water-cooling system is very complex. In all likelihood, a combined air–water-cooling system is the best choice.

Operational factors. The main advantage of SSEs over blade turbines is that the former are insensitive to quality of steam, which may have high wetness and even contain solid particles (scale and the like), since the flow between the rotors has a low velocity. Thus, the surfaces of the rotors do not suffer from erosion, nor is there any danger of the rotors becoming locked. Moreover, if the working medium contains various impurities, which deposit on the rotors and in the SSE shell, this results in even a somewhat higher efficiency of expansion as a result of smaller leaks through the gaps [2].

A steam screw-rotor machine, as a thermal engine, has a constant dependence of torque on the rotation frequency; therefore, an SSE has high maneuverability when it is changed to operate from one mode to another. The time taken to heat the machine when it is started from the cold state is around 15 min; the unit does not require a barring gear, and its shutdown takes no time.

A very important feature is that the power installation (an SSE with a generator) has small overall dimensions: for example, the PVM-2000 with the AG measures $3600 \times 1300 \times 1500$ mm, a size that allows the installation to be placed in a boiler house easily enough.

A steam screw-rotor machine features high operational reliability and safety. In a critical event, for example if the ACPS fails and the power network is disconnected followed by a rapid rise of the rotation frequency, the rotors will not be destroyed; in the worst case, they can be locked. The machine and the generator should be placed in a sound-insulating housing; in this case, the level of noise from the fan operation will not exceed 75 dB [3].

Maintenance. The shift operators of the boiler house supervise the power unit operation on a round-the-clock basis; in doing so, they do not need to continuously watch the display screen. If any malfunction occurs, the ACPS will shut down the SSE without any loss to it or to the main production process.

Economic factors. The payback period of a power installation built around an SSE is, as a rule, 1.5–2.5 years. The net cost of the own generated electricity is 0.2–0.25 rubles/(kW h), i.e., approximately the factor of 4–5 lower than it is at RAO Unified Energy Systems of Russia.

Thus, generation of electricity using an SSE immediately at a steam boiler house for partially covering the own needs of an enterprise is one of the promising lines of energy conservation.

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